

Measuring the Virial Masses of Disk Galaxies

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Abstract. I present detailed models for the formation of disk galaxies, and investigate which observables are best suited as virial mass estimators. Contrary to naive expectations, the luminosities and circular velocities of disk galaxies are extremely poor indicators of total virial mass. Instead, I show that the product of disk scale length and rotation velocity squared yields a much more robust estimate. Finally, I show how this estimator may be used to put limits on the efficiencies of cooling and feedback during the process of galaxy formation.

1 Introduction

Currently, the main uncertainties in our picture of galaxy formation are related to the intricate processes of cooling, star formation, and feedback. The cooling and feedback efficiencies are ultimately responsible for setting the galaxy mass fractions $f_{\text{gal}} = M_{\text{gal}}/M_{\text{vir}}$. Here M_{gal} is the total *baryonic* mass of the galaxy (stars plus gas, excluding the hot gas in the halo) and M_{vir} is the total virial mass.

Here I present new models for the formation of disk galaxies, which I use to investigate how well observables *extracted directly from these models* can be used to recover $f_{\text{gal}}(M_{\text{vir}})$. Even though the assumptions underlying the model are not necessarily correct, and the phenomenological descriptions of star formation and feedback are certainly oversimplified, this provides useful insights regarding the ability of actual observations to constrain the poorly understood astrophysical processes of galaxy formation.

2 Short Description of Models

The main assumptions that characterize the framework of the models are the following: (i) dark matter halos around disk galaxies grow by the smooth accretion of mass, (ii) in the absence of cooling the baryons have the same distribution of mass and angular momentum as the dark matter, and (iii) the baryons conserve their specific angular momentum when they cool. I follow Firmani & Avila-Reese (2000) and make the additional assumptions that (iv) the spin parameter of a given galaxy is constant with time, (v) each mass shell that virializes is in solid body rotation, and (vi) the rotation axes of all shells are aligned. Although neither of these assumptions is necessarily accurate, it was shown in van den Bosch

(2001) that they result in halo angular momentum profiles in excellent agreement with the high resolution N -body simulations of Bullock et al. (2001).

The main outline of the models is as follows. I set up a radial grid between $r = 0$ and the present day virial radius of the model galaxy and follow the formation and evolution of the disk galaxy using a few hundred time steps. Six mass components are considered: dark matter, hot gas, disk mass (both in stars and in cold gas), bulge mass, and mass ejected by outflows from the disk. The dark matter, hot gas, and bulge mass are assumed to be distributed in spherical shells, whereas the disk stars and cold gas are assumed to be in infinitesimally thin annuli. Each time step the changes in these various mass components in each radial bin are computed using the following prescriptions.

- The rate at which the total virial mass grows with time is given by the Universal mass accretion history (van den Bosch 2002a).
- At each redshift, the dark matter is assumed to follow an NFW density distribution (Navarro, Frenk & White 1997).
- The gas that enters the virial radius of a halo is added to the disk a time $t_c \equiv \max[t_{\text{ff}}, t_{\text{cool}}]$ later, where t_{ff} and t_{cool} correspond to the free-fall time and cooling time. The cooling time depends on the metallicity of the hot gas, which is taken to be a free parameter Z_{hot} .
- The radius at which the gas settles is governed by its specific angular momentum distribution, which follows from the assumptions (iv)–(vi) listed above.
- When the disk becomes unstable, part of the disk material is converted into a bulge component (cf. van den Bosch 1998).
- In the disk, only the cold gas with a surface density above the critical density given by Toomre’s stability criterion is considered eligible for star formation. This gas is transformed into stars with a rate given by a simple Schmidt law.
- Part of the cold gas is expelled from the system by supernovae feedback. This is modeled as in van den Bosch (2000), and regulated by a free feedback efficiency parameter ϵ_{fb} .

More details regarding these models can be found in van den Bosch (2001), where it is shown that these models yield disk galaxies in good agreement with observations. For instance, for the majority of the model galaxies the disk reveals an exponential surface brightness profile. Note that contrary to previous disk formation models (e.g., Mo, Mao & White 1998), this is not an *a priori* assumption of the model.

3 Galaxy Mass Fractions

In order to investigate how $f_{\text{gal}}(M_{\text{vir}})$ relates to the cooling and feedback efficiencies I discuss three models that only differ in the metallicity of the hot gas, Z_{hot} , and the feedback efficiency, ϵ_{fb} : the ‘Standard Model’ with $Z_{\text{hot}} = 0.3Z_{\odot}$ (a typical value for the hot gas in clusters) and $\epsilon_{\text{fb}} = 0$ (i.e., no feedback), the ‘Zero Metallicity Model’ with $Z_{\text{hot}} = 0.0$ and $\epsilon_{\text{fb}} = 0$, and the ‘Feedback Model’

with $Z_{\text{hot}} = 0.3Z_{\odot}$ and $\varepsilon_{\text{fb}} = 0.02$ (i.e., two percent of the SN energy is converted to kinetic energy). All other model parameters are kept fixed at their fiducial values (see van den Bosch 2001). For each model a sample of 400 model galaxies is constructed. Present day virial masses are drawn from the Press-Schechter mass function with $10^{10}h^{-1} M_{\odot} \leq M_{\text{vir}}(0) \leq 10^{13}h^{-1} M_{\odot}$, corresponding to $31 \text{ km s}^{-1} \leq V_{\text{vir}} \leq 312 \text{ km s}^{-1}$, roughly the range expected for galaxies. Spin parameters, which parameterize the specific angular momentum, are drawn from a typical log-normal distribution.

Figure 1 plots the present day galaxy mass fractions $f_{\text{gal}} = M_{\text{gal}}/M_{\text{vir}}$ as function of M_{vir} (crosses). In the models without feedback f_{gal} is virtually identical to the universal baryon fraction f_{bar} for low mass systems. For more massive systems, cooling becomes inefficient, causing f_{gal} to strongly decrease with increasing virial mass. This is more pronounced in the model with $Z_{\text{hot}} = 0$, for which cooling is least efficient. In the Feedback Model (right panel), $f_{\text{gal}} \ll f_{\text{bar}}$ for the low mass systems, but with a large amount of scatter. This is a reflection of the scatter in halo spin parameters: systems with less angular momentum produce disks with higher surface densities, therefore have higher star formation rates, which induce a more efficient feedback. At the high mass end f_{gal} is fairly similar to the Standard Model without feedback. This owes to the fact that the mass ejection efficiency scales inversely with the square of the escape velocity, making feedback less efficient in more massive systems.

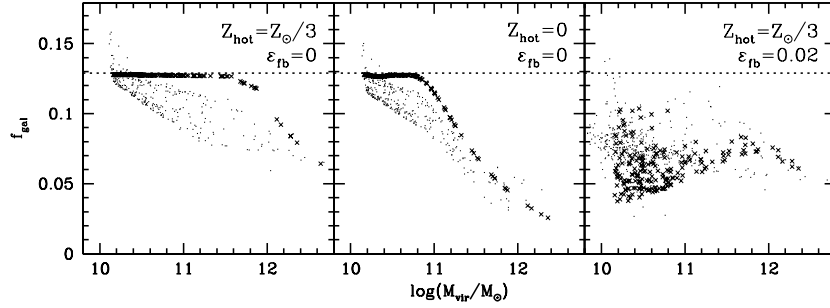


Fig. 1. A comparison of the true galaxy mass fraction f_{gal} as function of the true virial mass (crosses) with the same values estimated from the observables extracted from the models (dots). Results are plotted for all three models discussed in the text. The horizontal dotted line corresponds to the universal baryonic mass fraction f_{bar} . In the model with feedback (right panel) the dots occupy the same parameter space as the crosses, indicating that the observables allow one to recover $f_{\text{gal}}(M_{\text{vir}})$, at least in a statistical sense. In the two models without feedback there are significant errors in the recovered $f_{\text{gal}}(M_{\text{vir}})$. Yet, the two $f_{\text{gal}}(M_{\text{vir}})$ are sufficiently different to discriminate between the two models; in particular, the estimated galaxy mass fractions nicely avoid the upper right regions of parameter space which contain information on the cooling efficiencies. Furthermore, the dots occupy different areas of parameter space in models with and without feedback, such that there is hope that the “observed” $f_{\text{gal}}(M_{\text{vir}})$ may be used to constrain the efficiency of feedback.

Clearly $f_{\text{gal}}(M_{\text{vir}})$ depends strongly on both the cooling and feedback efficiencies. Therefore, if one could obtain a measure of $f_{\text{gal}}(M_{\text{vir}})$ observationally it would allow us to constrain the poorly understood physics of cooling and feedback. This requires one to be able to infer both the baryonic galaxy mass M_{gal} as well as the total virial mass M_{vir} from observations of the luminous (and gaseous) components. Using the models outlined above I now investigate which observables are best suited as the appropriate mass indicators.

For the galaxy mass one can write $M_{\text{gal}} = \Upsilon_B L_B + M_{\text{gas}}$. Here L_B is the total B -band luminosity, Υ_B is the corresponding stellar mass-to-light ratio, and M_{gas} is the galaxy's (cold) gas mass. L_B is easily obtained observationally, and I assume that M_{gas} is observationally accessible through HI measurements. The stellar mass-to-light ratio, however, is not directly accessible to an observer, but has been shown to correlate strongly with color. I therefore extract the $B - K$ color from the models from which I estimate Υ_B using the relation of Bell & de Jong (2001).

The galaxy virial mass is more difficult to obtain. In Figure 2 I plot three ‘observables’ as function of M_{vir} for galaxies in each of the three models. Note that both V_{max} , defined as the maximum rotation velocity inside the radial extent probed by the cold gas, and L_K are poor indicators of virial mass. First of all the slope and zero-points of the $V_{\text{max}}(M_{\text{vir}})$ and $L_K(M_{\text{vir}})$ relations depend on the input parameters of the model. This means that an observer trying to infer M_{vir} from either V_{max} or L_K needs to make assumptions about the efficiencies of cooling and feedback. However, it is exactly these efficiencies that we seek to constrain. Secondly, the scatter of both relations can be so large that even if the normalization of the relation were known, one could still not infer M_{vir} to better than an order of magnitude. In particular, the scatter in $V_{\text{max}}(M_{\text{vir}})$ can be very large. This owes entirely to the scatter in halo spin parameter, which sets the concentration of the baryonic mass component after cooling, therewith strongly influencing V_{max} .

As the lower panels in Figure 2 show, a much more reliable virial mass indicator is $R_d V_{\text{max}}^2 / G$. Here R_d is the disk scale length in the I -band, obtained from fitting an exponential to the I -band surface brightness distribution of the disk. Upon fitting all galaxies of all three models simultaneously I obtain

$$M_{\text{vir}} = 2.54 \times 10^{10} \text{ M}_{\odot} \left(\frac{R_d}{\text{kpc}} \right) \left(\frac{V_{\text{max}}}{100 \text{ km s}^{-1}} \right)^2. \quad (1)$$

(rms scatter between 20 and 50 percent, depending on the amount of feedback). The fraction of model galaxies for which equation (1) yields an estimate of the true virial mass to better than a factor two is larger than 97 percent! It is remarkable that the zero-point for models with feedback is the same as for models without feedback. When matter is ejected it reduces V_{max} but at the same time increases the disk scale length such that $R_d V_{\text{max}}^2$ stays roughly constant. This is due to the star formation threshold criterion included in the models. If real galaxies follow a similar threshold criterion, equation (1) provides a fairly accurate estimate of the total virial mass of disk galaxies.

We now have all the tools in place to see whether we can recover $f_{\text{gal}}(M_{\text{vir}})$ from the “observables”. The dots in Figure 1 correspond to the estimates of $f_{\text{gal}}(M_{\text{vir}})$ obtained using the method outlined above. In both models without feedback there are significant errors in the recovered $f_{\text{gal}}(M_{\text{vir}})$, which is dominated by errors in the estimate of M_{vir} . Yet, the recovered $f_{\text{gal}}(M_{\text{vir}})$ of the two models are sufficiently different to distinguish between them. In particular, in both models the dots avoid the regions in the upper right corner which contains information about the efficiency of cooling. In the feedback model the recovered values occupy roughly the same area of the $f_{\text{gal}} - M_{\text{vir}}$ plane as the intrinsic values. Although the one-to-one correspondence for individual model galaxies may be poor, statistically the method to recover $f_{\text{gal}}(M_{\text{vir}})$ explored here works reasonably well.

4 Conclusions

We have shown that the product of disk scale length and maximum rotation velocity squared can be used as a fairly accurate estimator of total virial mass. This in turn can be used to obtain estimates of the galaxy mass fractions as function of virial mass, which contains important information about the efficiencies of cooling and feedback. Another approach, that has been taken in the past, is to use published luminosity functions and luminosity-velocity relations to construct halo velocity functions (i.e., Newman & Davis 2000; Gonzales et al. 2000; Kochanek 2001). The main goal of these studies is similar to the work presented here, namely to circumvent the problems with poorly understood astrophysical processes when linking the observed properties of galaxies to those of their dark matter halos. Our results imply that great care is to be taken in linking an observable velocity such as V_{max} to the circular velocity of a dark matter halo. Based on our results, we suggest that the construction of a halo *mass* function using $M_{\text{vir}} \propto R_d V_{\text{max}}^2$ may prove more reliable. More details of the results presented here can be found in van den Bosch (2002b).

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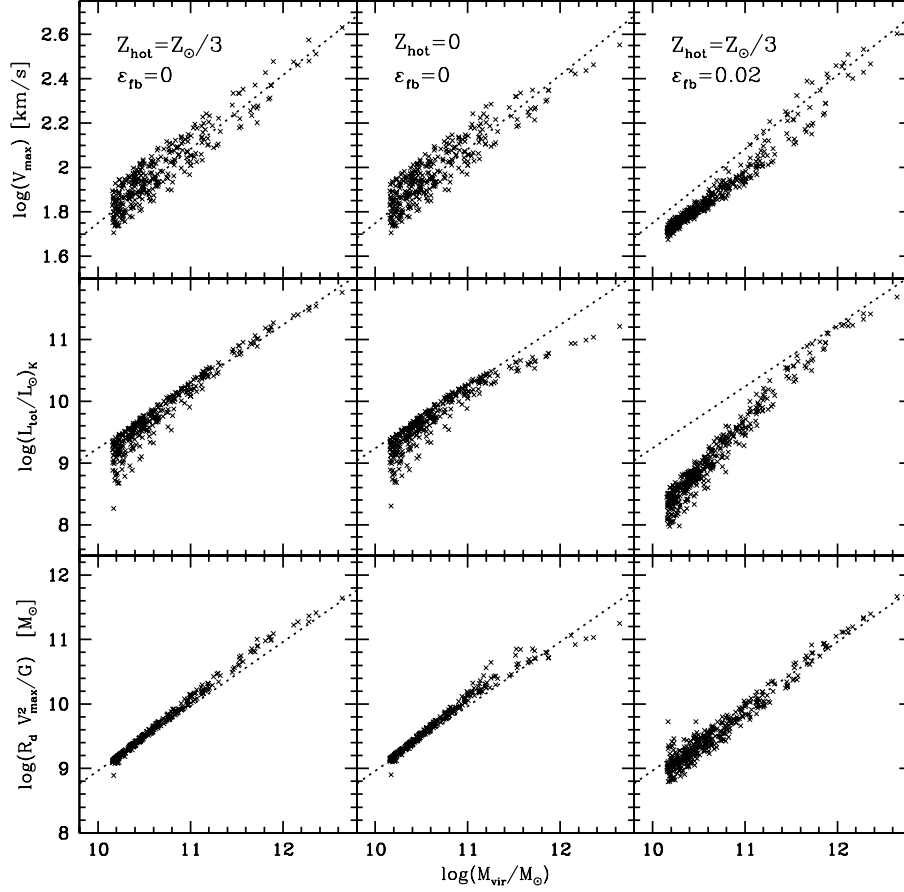


Fig. 2. The relation between various virial mass estimators and the actual virial mass for all three models. In the upper panels $\log(V_{\max})$ is plotted versus $\log(M_{\text{vir}})$. The dotted line corresponds to $M_{\text{vir}} \propto V_{\max}^{1/3}$, which is a reasonable description of the average relation. However, the scatter is large, and the zero-point depends on the actual model, which makes V_{\max} unsuitable as virial mass indicator. The same goes for the K -band luminosity, which is plotted in the middle row of panels. Here the dotted line corresponds to $L_K \propto M_{\text{vir}}$, which only yields a reasonable description for the brighter galaxies in models with $Z_{\text{hot}} = Z_{\odot}/3$. For fainter galaxies, however, the scatter is large. Furthermore the slope of the $L_K(V_{\text{vir}})$ relation depends strongly on the feedback efficiency. Thus total luminosity is also a poor indicator of total virial mass. The lower panels plot the virial mass estimator $R_d V_{\max}^2 / G$ as function of M_{vir} . Here the dotted lines correspond to equation (1), which gives a reasonable fit to the model galaxies, independent of the cooling and/or feedback efficiencies. In addition, the scatter is relatively small, making the product of disk scale length and maximum rotation velocity squared a fairly accurate estimator of total virial mass.